Resent results and current status of the muon g−2 experiment at BNL

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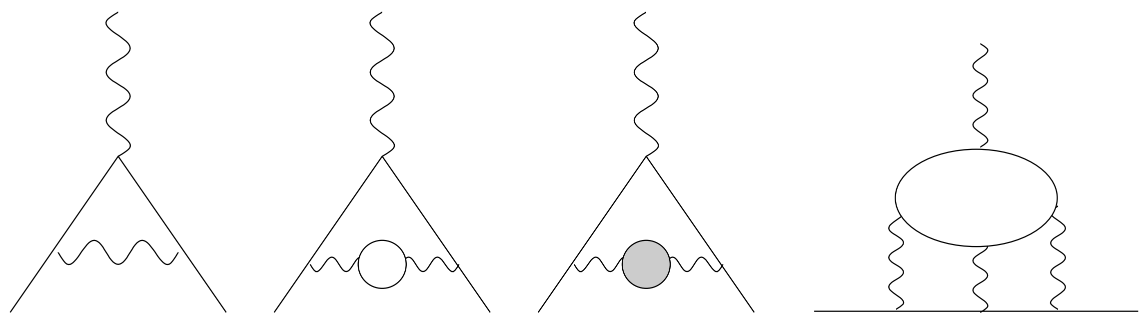
Muon g–Factor

- The magnetic moment of a particle $\vec{\mu}$ is related to its intrinsic spin $\vec{S}$ via the gyromagnetic ratio g:

$$\vec{\mu} = g \, \frac{e\hbar}{2mc} \, \vec{S}$$

- For a spin $\frac{1}{2}$ Dirac particle, $g = 2$

- But, value of g is modified by quantum field fluctuations (radiative corrections):

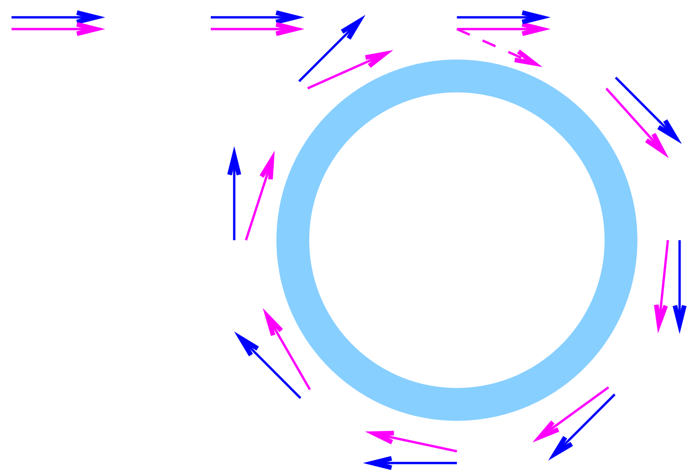


- Precision measurement of $a_\mu = \frac{1}{2}(g_\mu - 2)$ probes short–distance structure of the theory and provides:
  - Stringent test of the Standard Model
  - Search for New Physics

Measuring a_μ

Measure the spin precession frequency relative to the momentum vector for a muon in a uniform magnetic field:

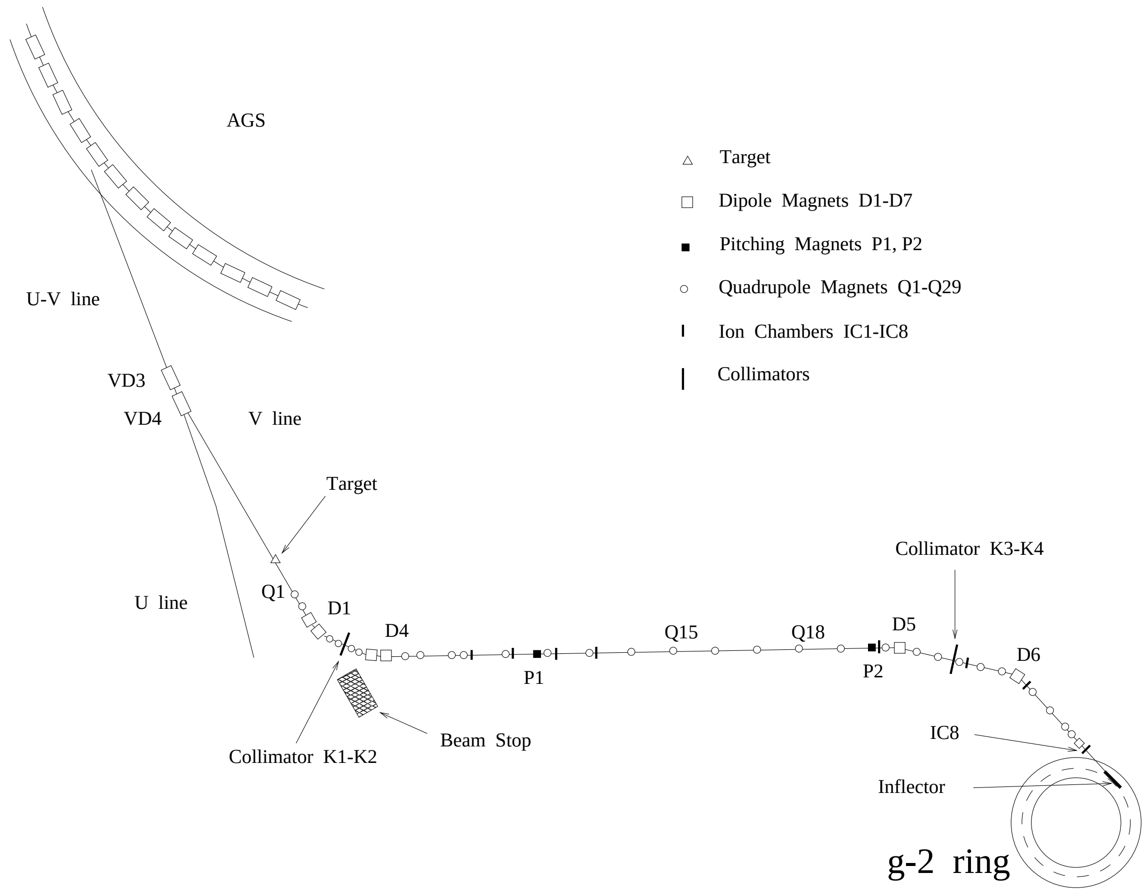
$$\omega_a = \omega_s - \omega_c = \left[g\frac{eB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc} \right] - \frac{eB}{\gamma mc} = a_\mu \frac{eB}{mc}$$



For this measurement we use:

- Polarized muons from parity violating decay $\pi \to \mu + \nu_\mu$ (select highest energy muons)
- Muon precession in a uniform magnetic field of storage ring, up to 10 muon lifetimes
- Electrons from parity violating decay $\mu \to e + \overline{\nu}_e + \nu_\mu$ as a polarimeter (select high energy electrons)

G–2 Beam Line



* $\sim 40 \cdot 10^{12}$ **protons at the target every 2.6 seconds,** $\mathbf{P_p = 24}$ **Gev/c.**

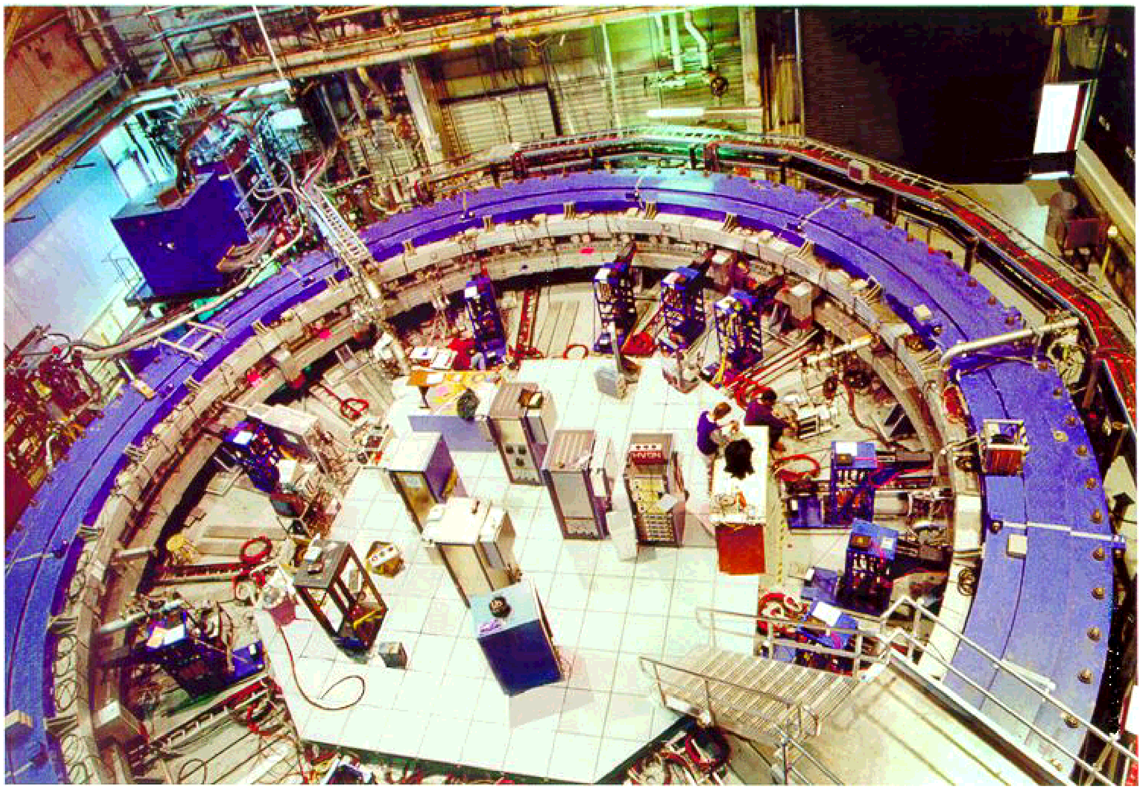
* **Distance between target and inflector: 122 m.**

* **Pion injection:** $\mathbf{P_\pi}$**=3.15 GeV/c,** $c\,\tau\,\gamma$**=174 m.**
  2.6$\cdot 10^7\ \pi$ **per** 10^{12} **protons at the target.**

* **Distance between pion selecting and pion rejection slits: 97.5 m.**

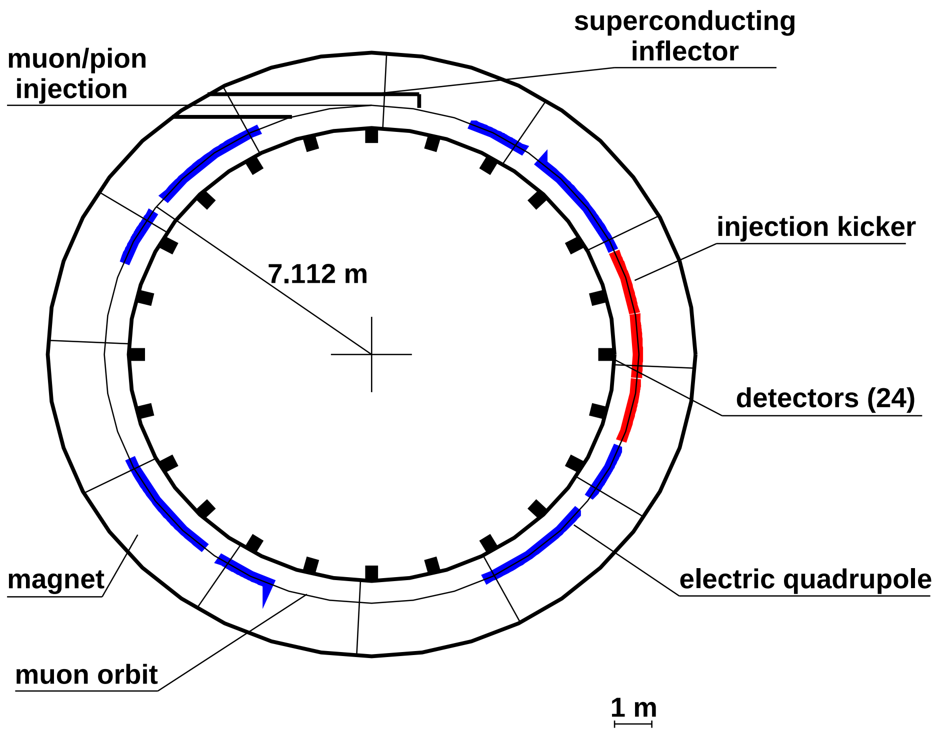
* **Muon injection:** $\mathbf{P_\mu}$**=3.094 GeV/c,**
  $10^5\ \mu$ **per** 10^{12} **protons at the target.**

Muon Storage Ring



* Radius of central orbit :	711.2	cm
* Magnetic field :	1.45	T
* Muon momentum :	3.094	GeV/c
* Cyclotron period :	0.149	μsec
* Muon lab lifetime :	64.4	μsec
* Period of (g–2) oscillations :	4.37	μsec

BNL Muon g-2 Experiment



$$\omega_a = \omega_s - \omega_c = \frac{e}{mc} a_\mu B$$

$$\omega_a = \frac{e}{mc}\left[a_\mu B - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \vec{E})\right], \quad \text{if} \quad \vec{E} \neq 0$$

We choose "magic" $\gamma = 29.3$, $p = 3.09$ GeV/c to vanish (...) and get ω_a to be independent of E. Then we use

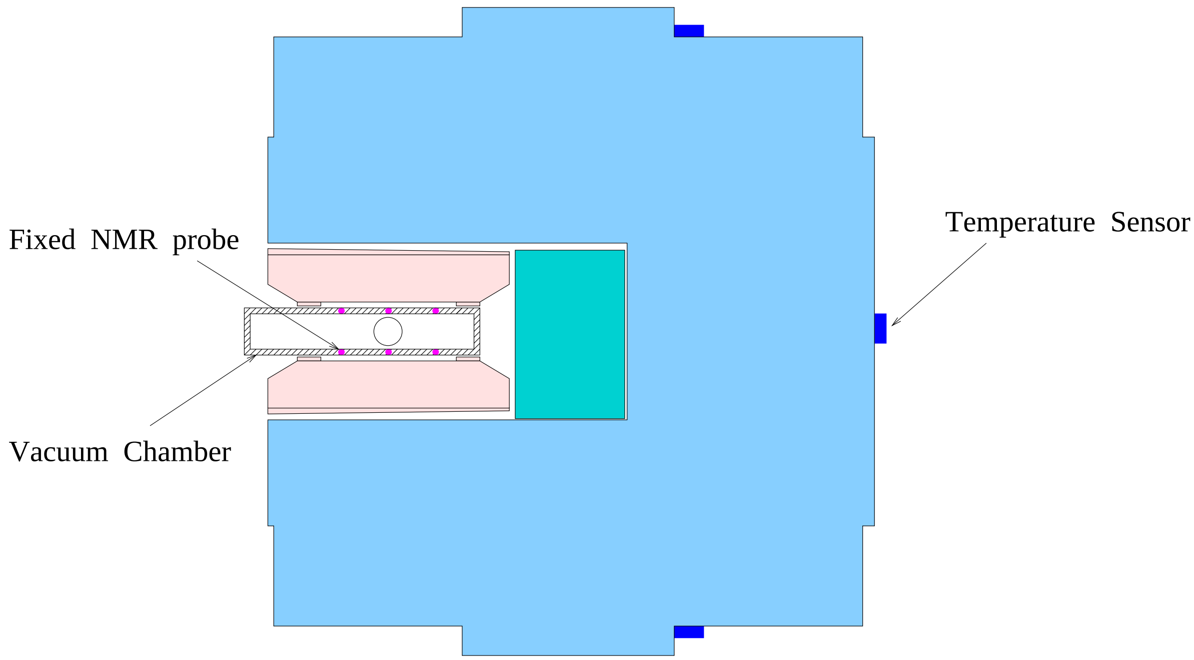
- Uniform magnetic field for precise measurement of a_μ
- Quadrupole $E-$field for vertical focusing of muon beam

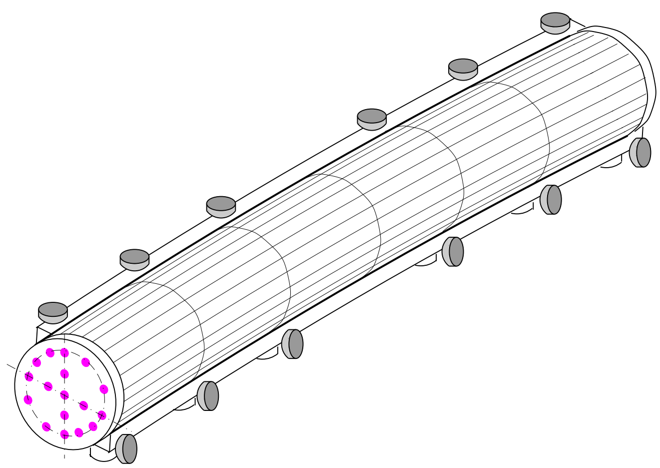
$B-$field is measured by a proton NMR frequency ω_p, thus ratios ω_a/ω_p and μ_μ/μ_p can be used:

$$\frac{\mu_\mu}{\mu_p} = \frac{\omega_s(rest)}{\omega_p} = g\,\frac{eB}{2\,mc\,\omega_p} = g\,\frac{\omega_a}{2\,a_\mu\,\omega_p} = \frac{1 + a_\mu}{a_\mu}\,\frac{\omega_a}{\omega_p}, \quad \text{hence}$$

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}, \qquad \mu_\mu/\mu_p = 3.183\,345\,39\,(10)\,(0.03\text{ ppm})$$

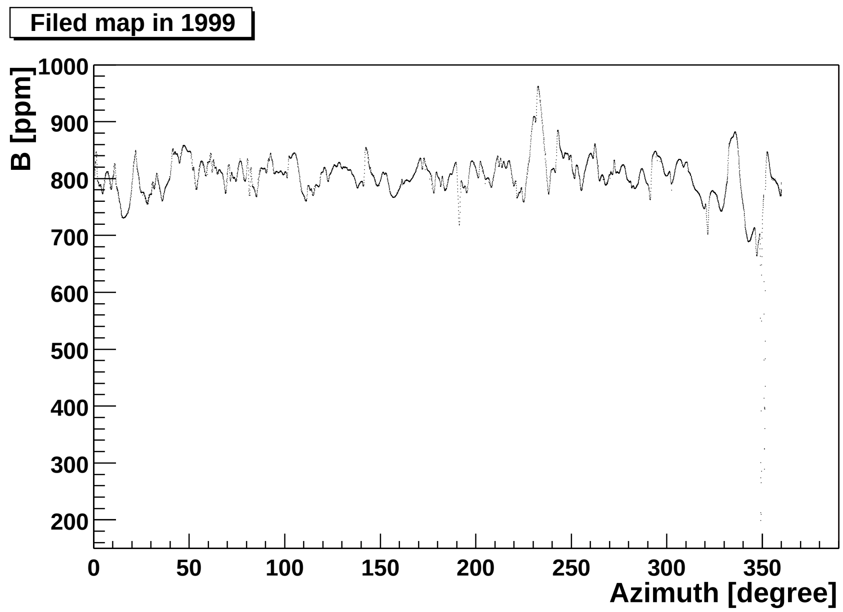
NMR system

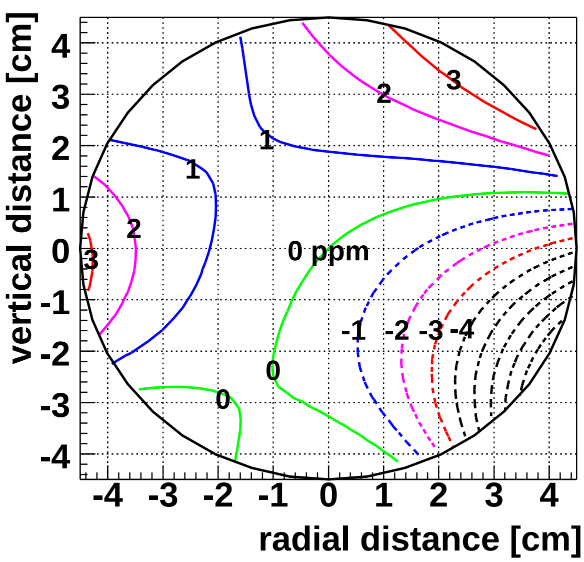




- 17 NMR probes mounted on the beam tube trolley and used to record field map every 2-3 days
- 366 fixed probes embedded in the vacuum chamber walls
- about 150 fixed probes used to interpolate B field between trolley runs
- power supply of the magnet is stabilized by feedback from average of 36 fixed probes' readings

Magnetic Field





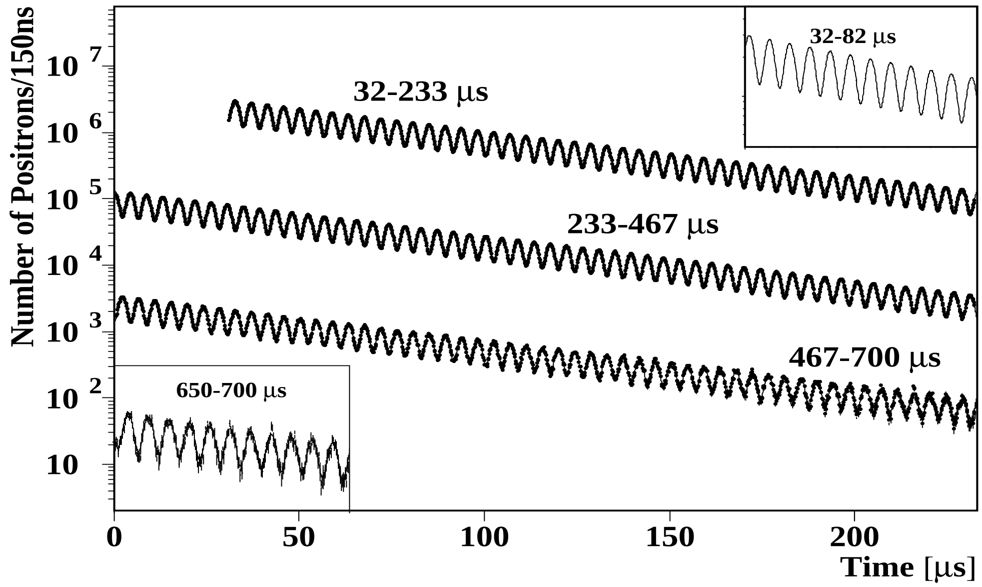
Multipoles [ppm]

	normal	skew
Quad	-2.2(1)	2.2(1)
Sext	-1.1(1)	2.5(2)
Octu	-1.3(2)	1.9(2)
Decu	0.9(2)	1.0(3)

A 2-dimensional multipole expansion of the field averaged over azimuth from one out of seventeen trolley measurements. One ppm contours are shown with respect to a central azimuthal average field $B_0 = 1.451\ 266$ T. The circle indicates the muon beam storage region. The multipole amplitudes at the beam aperture radius of 4.5 cm are given.

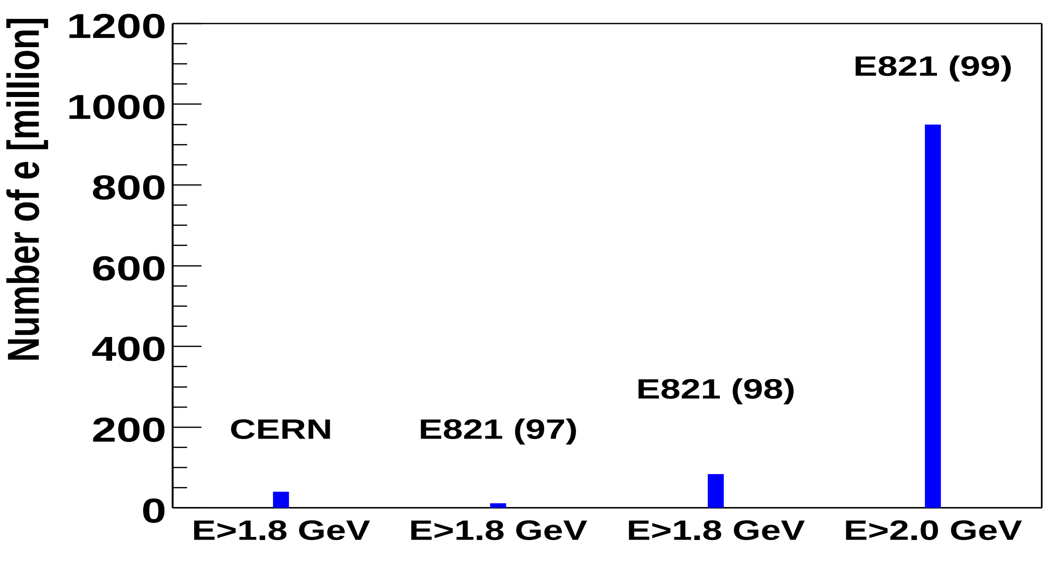
g-2 Data (ω_a)

E821(99) : 0.95×10^9 positrons with $E \geq 2.0$ GeV



Time spectrum of decay positrons is basically the exponentially decaying sine wave: $f(t) = N_\circ e^{-t/\tau}\ [1 + A\sin(\omega_a t + \phi_a)]$ with period $T_a = 2\pi/\omega_a = 4.37\,\mu$s and lifetime $\tau = \gamma\tau_\circ = 64.4\,\mu$s. However, the spectrum is slightly distorted by

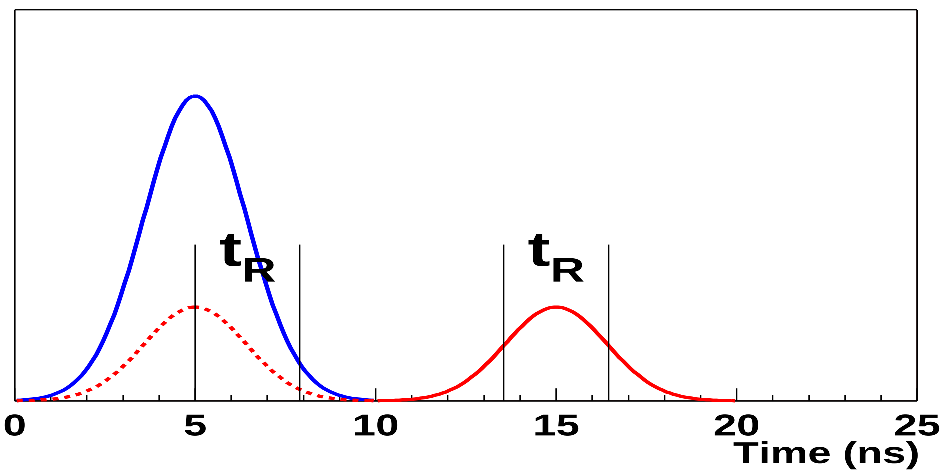
- pileup (pulses overlapping in time),
- coherent betatron oscillations (CBO) and
- muon losses



Pileup Subtraction

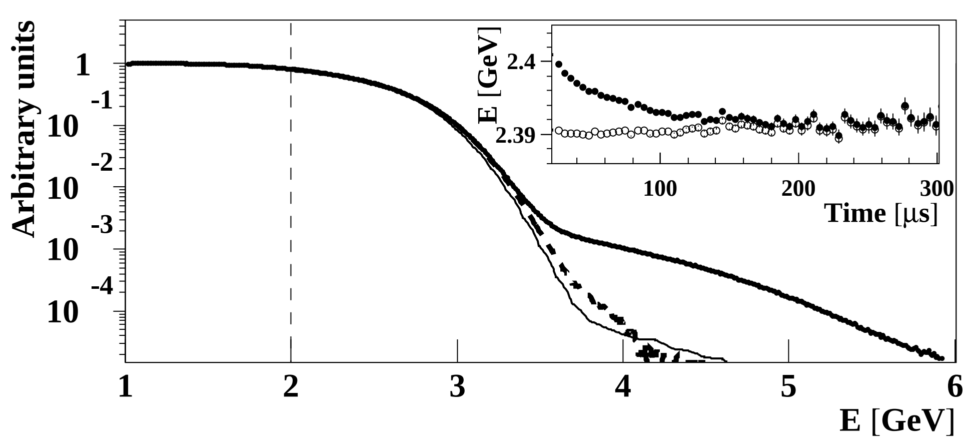
The pileup is proportional to e^+ rate squared, it's level is $\sim$ 1% at 30 μs after the muon injection. Pileup contribution can be estimated (and subsequently subtracted) from the data.

On the picture: probability to have a pileup pulse (red dash line) within time resulution t_R on a given recorded pulse (blue line) can be estimated by searching for another recorded pulse (red line) at the time window t_R some fixed time before or after the first.



Pileup subtraction procedure can be checked by the energy spectrum correction:

On the picture: the energy spectrum of the detected positrons above 1 GeV at all times (thick line) and at only late times (thin line) together with the pileup-subtracted spectrum at all times (dashed line). The inset shows the energy above 2 GeV averaged over one $g-2$ period as a function of time before (filled circles) and after (open circles) pileup subtraction for a typical detector.



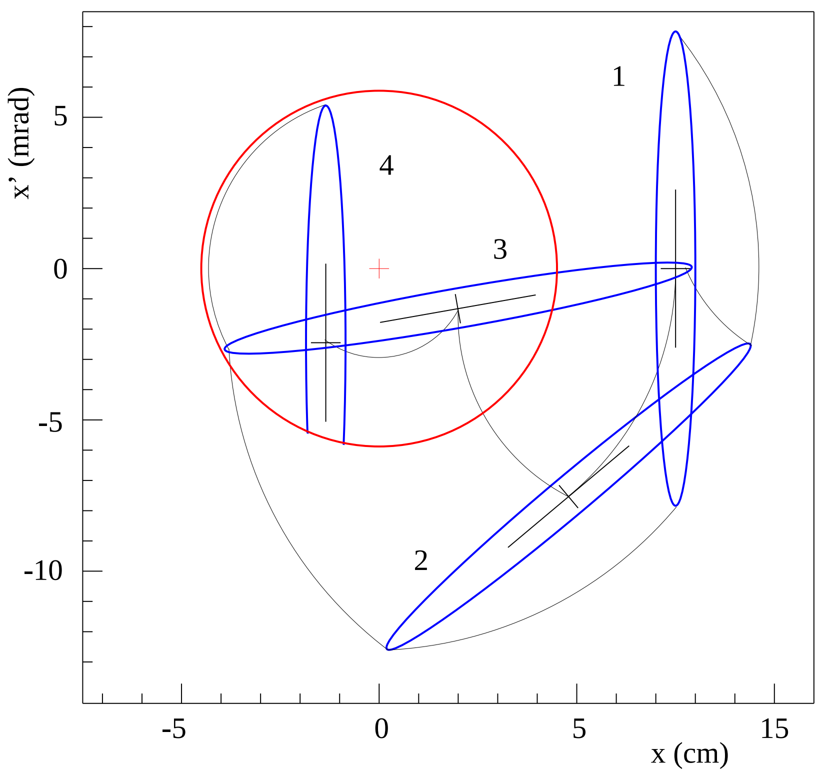
Radial Betatron Oscillations

$$x = x_\circ + A\cos\left(\frac{\nu_x\, s}{R} + \phi\right)$$

$$x' = \frac{A\,\nu_x}{R}\sin\left(\frac{\nu_x\, s}{R} + \phi\right) \qquad \nu_x = \sqrt{1-n} = 0.93$$

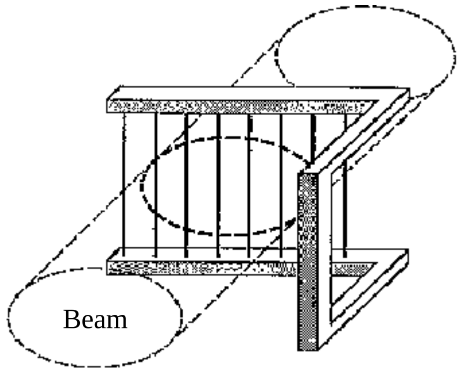
For direct muon injection:
due to inflector geometry and imperfect kick, the stored muon beam does not fill available phase space uniformly. In general, center of gravity of muon distribution is off center of storage volume and oscillates around it with period of $\nu_x^{-1} = 1.07$ in units of cyclotron period.

Phase–space plot for beam storage and betatron oscillations:

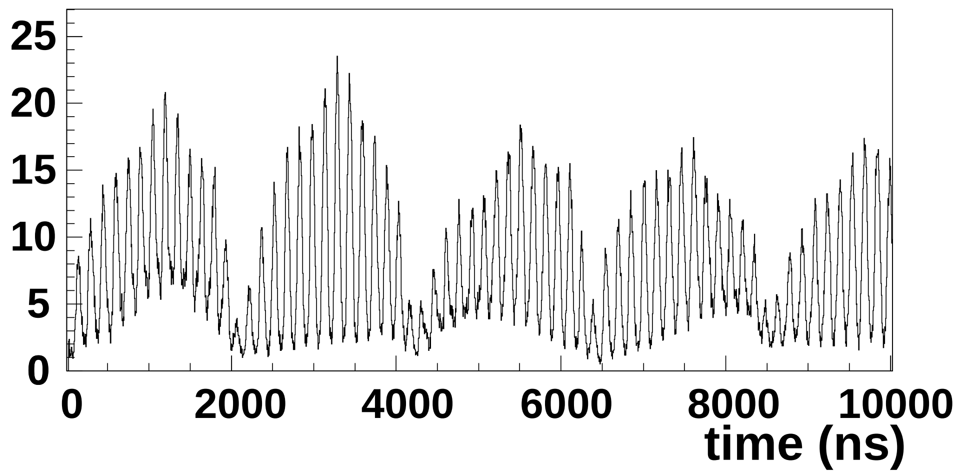


On the picture: muon distribution at the inflector exit (1), at the kicker entrance (2), at the kicker exit (3) and get stored (4), consequently.

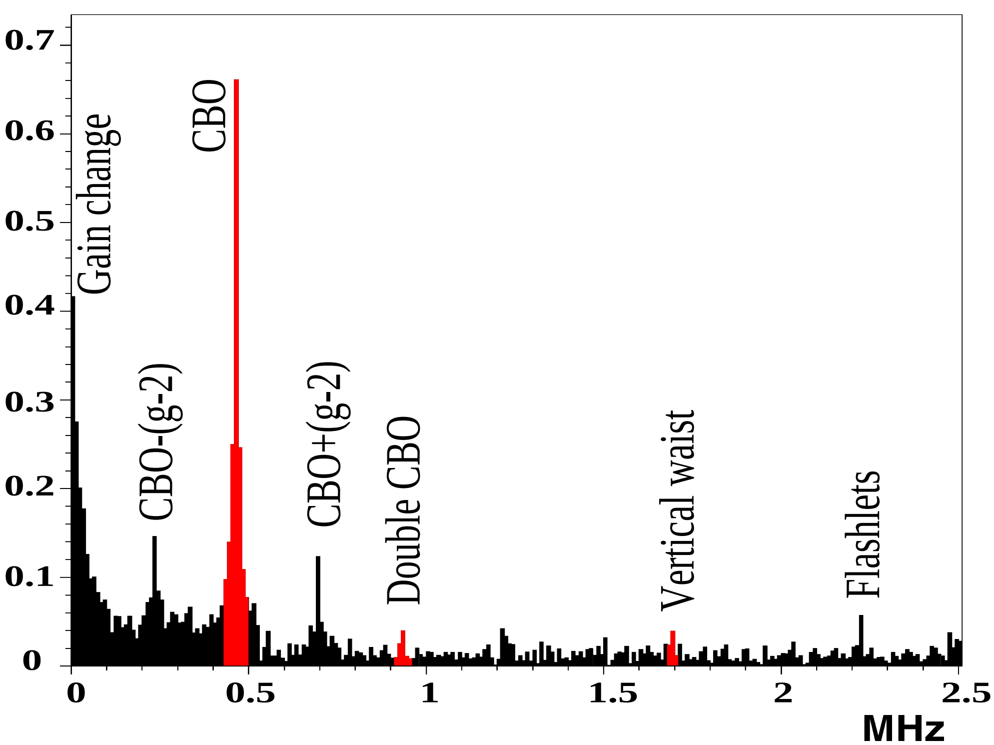
Coherent Betatron Oscillation



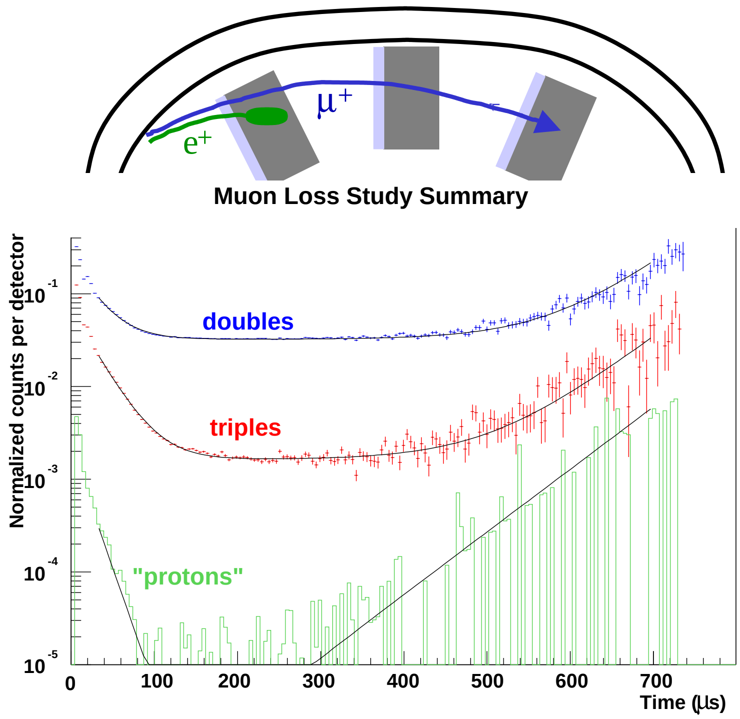
fiber monitor

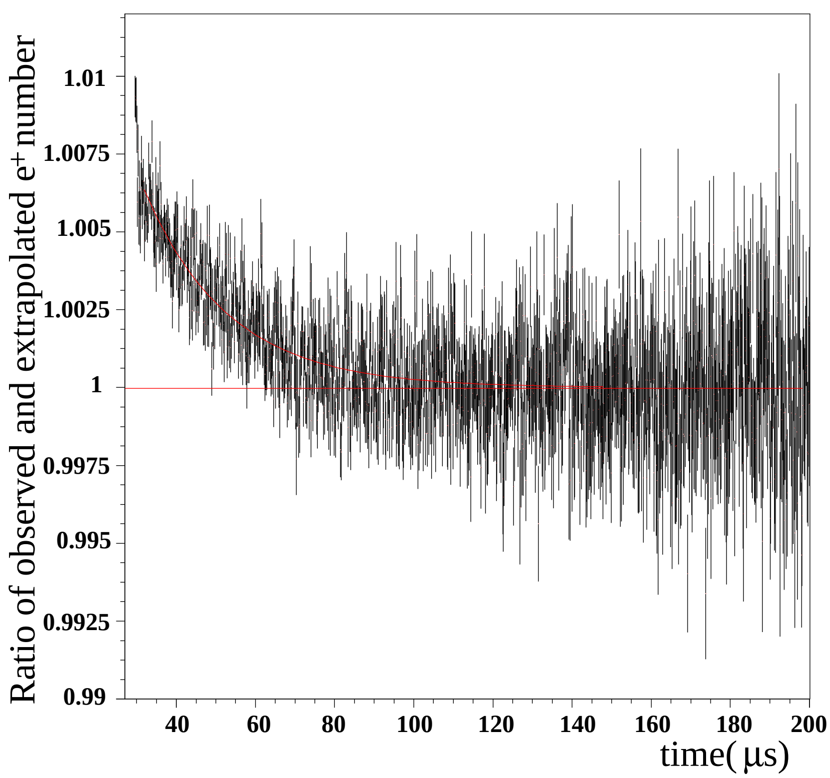


Fourier Analysis of the Residual from 5-par Fit



Muon Loss





The muon loss is: $l(t) = 1 + n_l\, e^{-t/\tau_l}$

$n_l = 0.006$ at 30 μs and $\tau_l = 27$ μs.

Fitting for ω_a

Pileup subtracted e^+ distribution was fitted with the 10 parameter function:

$$\begin{aligned} f(t) &= N_\circ \, e^{-t/\tau} \; [1 + A \sin(\omega_a t + \phi_a)] \\ &\times \left(1 + A_b \, e^{-t^2/\tau_b{}^2} \cos(\omega_b t + \phi_b)\right) \qquad - \text{CBO} \\ &\times \left(1 + n_l \, e^{-t/\tau_l}\right) \qquad - \text{muon loss} \end{aligned}$$

CBO frequency ω_b was found from Fourier analysis of residuals. Data and fit are in good agreement:
$\chi^2/d.o.f. = 3818/3799 = 1.005$

Four independent analyses have been done:

$$\frac{\omega_a(BNL)}{2\pi} = 229\ 072.65 \pm 0.28 \text{ Hz}$$

$$\frac{\omega_a(BU)}{2\pi} = 229\ 072.61 \pm 0.28 \text{ Hz}$$

$$\frac{\omega_a(IL)}{2\pi} = 229\ 072.60 \pm 0.28 \text{ Hz}$$

$$\frac{\omega_a(MN)}{2\pi} = 229\ 072.66 \pm 0.29 \text{ Hz}$$

<u>Final result :</u> $\frac{\omega_a}{2\pi} = 229\ 072.8 \pm 0.3$ Hz (1.3 ppm)

correction $+0.81 \pm 0.08$ ppm for effects of electric field and vertical betatron oscillations has been applied

Systematic Errors

Systematic errors for the ω_p analysis

Source of errors	Size [ppm]
Absolute calibration of standard probe	0.05
Calibration of trolley probes	0.20
Trolley measurements of B_0	0.10
Interpolation with fixed probes	0.15
Inflector fringe field	0.20
Uncertainty from muon distribution	0.12
Others †	0.15
Total systematic error on ω_p	0.4

† higher multipoles, trolley temperature and its power supply voltage response, and eddy currents from the kicker.

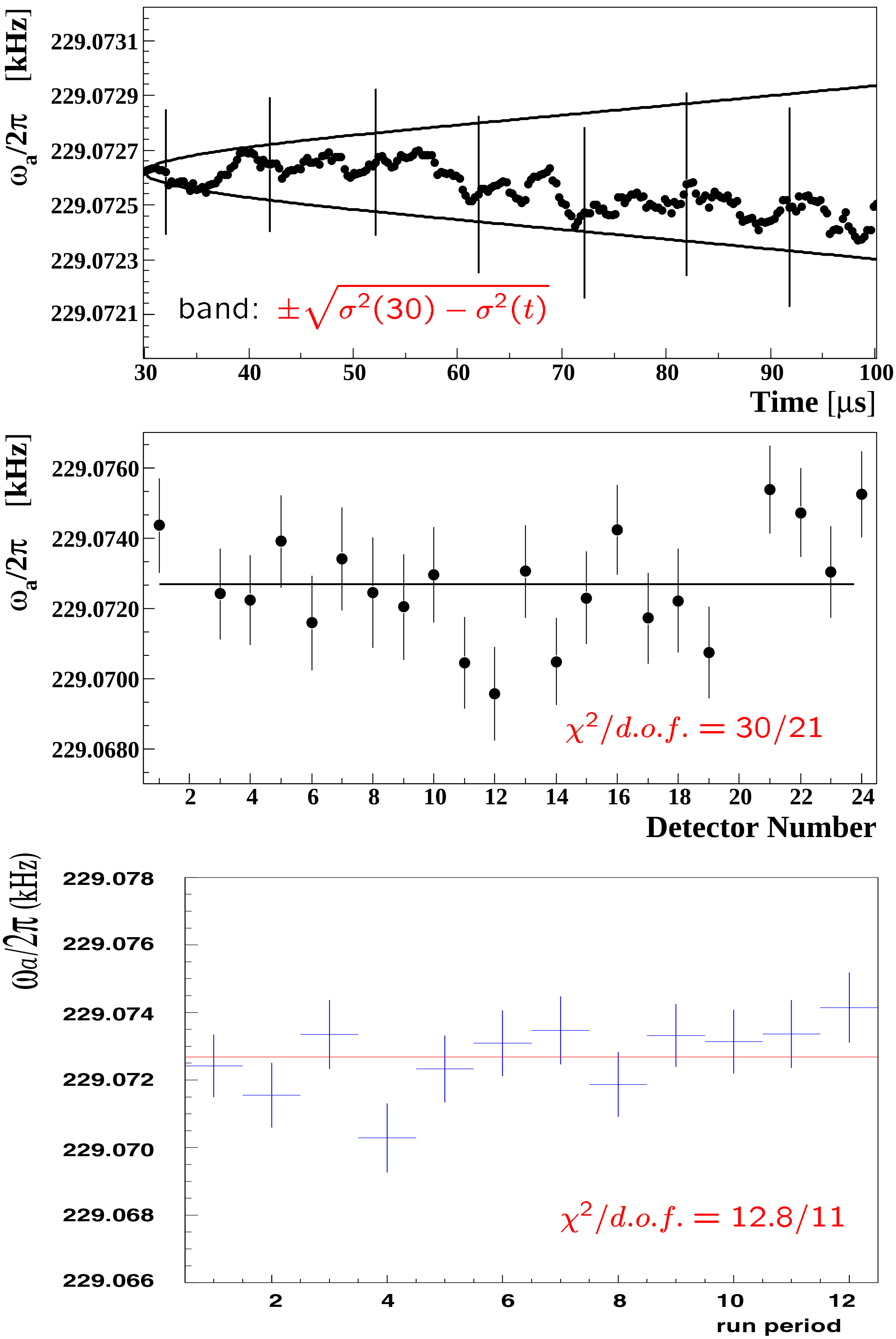
Systematic errors for the ω_a analysis

Source of errors	Size [ppm]
Pileup	0.13
AGS background	0.10
Lost muons	0.10
Timing shifts	0.10
E field and vertical betatron oscillation	0.08
Binning and fitting procedure	0.07
Coherent betatron oscillation	0.05
Beam debunching/randomization	0.04
Gain changes	0.02
Total systematic error on ω_a	0.3

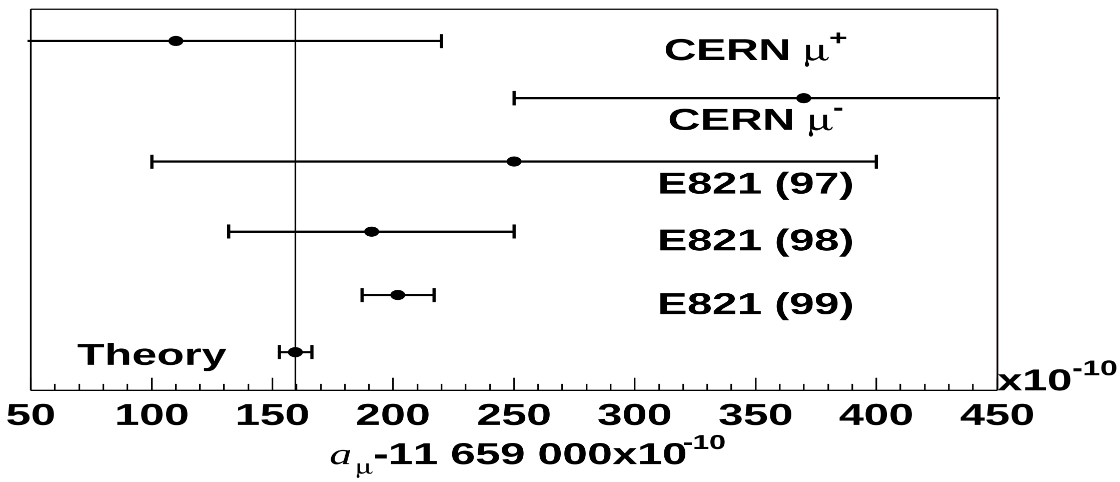
Systematics due to spin resonances, fit start time and clock synchronization are less than 0.01 ppm.

A correction of $+0.81 \pm 0.08$ ppm was applied for the effects of the electric field and vertical betatron oscillaitons.

ω_a stability



Results



$a_\mu(\text{exp}) = 11\ 659\ 203(15) \times 10^{-10}$ (1.3 ppm)

$a_\mu(\text{SM}) = 11\ 659\ 159.6(67) \times 10^{-10}$ (0.57 ppm)

$a_\mu(\text{exp}) - a_\mu(\text{SM}) = 43(16) \times 10^{-10}$ (2.6 sigma difference)

FURTHER PROGRESS:

Data set		Statistical error	Systematic error	Status
1999	1B μ^+	1.25 ppm	0.5 ppm	Published
2000	4B μ^+	0.63 ppm	0.4 ppm	Currently being analysed
2001	3B μ^-	0.72 ppm	0.3 ppm	Currently being analysed
2002	6B μ^-	0.51 ppm	0.3 ppm	Plan for new run

Total expected:

5B μ^+	0.56 ppm
9B μ^-	0.42 ppm
14B μ	0.33 ppm

Standard Model Prediction for a_μ

$$a_\mu(\mathrm{SM}) = a_\mu(\mathrm{QED}) + a_\mu(\mathrm{had}) + a_\mu(\mathrm{weak})$$

$$\begin{aligned} a_\mu(\mathrm{QED}) \quad = \quad & 0.5 \times (\alpha/\pi) \\ & + 0.765\ 857\ 388(44) \times (\alpha/\pi)^2 \\ & + 24.050\ 509(2) \times (\alpha/\pi)^3 \\ & + 126.04(41) \times (\alpha/\pi)^4 \\ & + 930(170) \times (\alpha/\pi)^5 \end{aligned}$$

$$= \quad 116\ 584\ 705.7(2.9) \times 10^{-11}$$

here $\alpha^{-1} = 137.035\ 999\ 59(40)$ from a_e measurement was used

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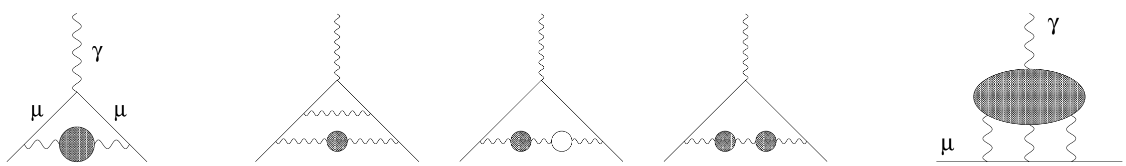
$$a_\mu(\mathrm{had}) \quad = \quad a_\mu(\mathrm{had}, 1) + a_\mu(\mathrm{had}, 2) + a_\mu(\mathrm{had}, \mathrm{lbls})$$



$$= \ \left[\ 6924(62)\ -\ 100(6)\ -\ 85(25)\ \right] \times 10^{-11}$$

$$a_\mu(\mathrm{weak}) \quad = \quad a_\mu(\mathrm{weak}, 1) + a_\mu(\mathrm{weak}, 2) + a_\mu(\mathrm{weak}, 3)$$

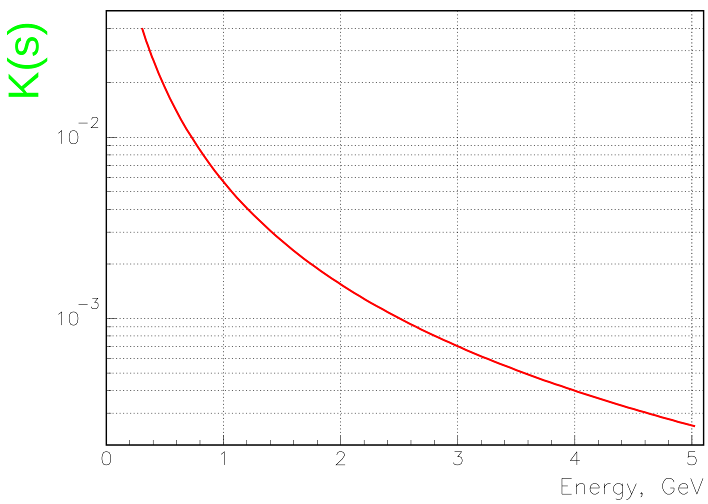
$$= \ \left[\ 195\ -\ 42(3)\ +\ 0.5\ \right] \times 10^{-11}$$

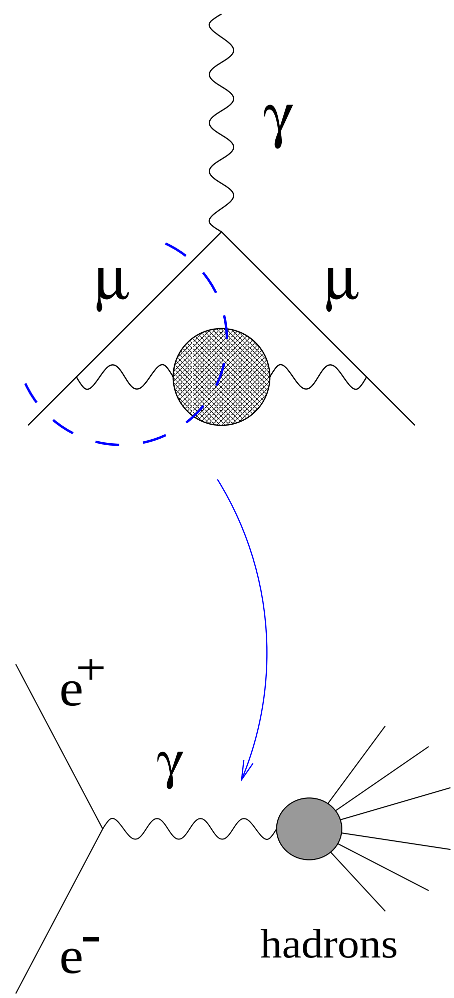
$$a_\mu(\mathrm{SM}) = 116\ 591\ 596(67) \times 10^{-11}$$

$a_\mu(had, 1)$

Strong QCD coupling at low energy precludes full QCD calculation, but $a_\mu(had; 1)$ can be found from experimental measurement of $e^+e^- \to hadrons$ cross section and the dispersion relation

$$a_\mu(had; 1) = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} ds \, \sigma_{e^+e^- \to hadrons}(s) \, K(s)$$

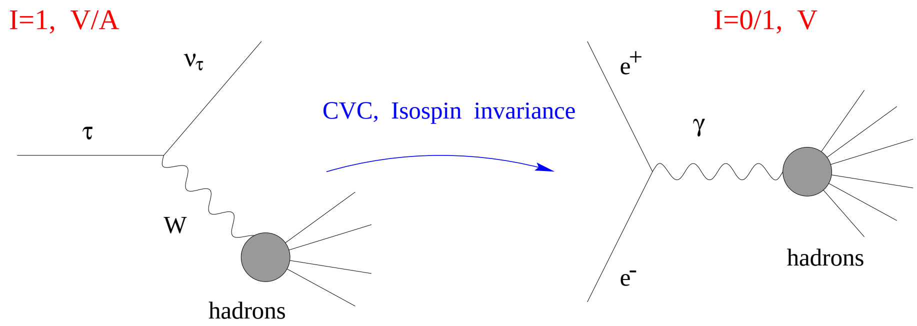




Mode	Energy	$a_\mu^{mode}(\sigma_{stat})(\sigma_{syst})$
$\pi^+\pi^-$	< 1.4 GeV	$5022\,(70)\;(88)\cdot 10^{-11}$
$\pi^+\pi^-\pi^\circ$	< 1.4 GeV	$509\,(15)\;(13)\cdot 10^{-11}$
K^+K^-	< 1.4 GeV	$251\,(10)\;(19)\cdot 10^{-11}$
$K_L K_S$	< 1.4 GeV	$148\;(2)\;(6)\cdot 10^{-11}$
$\omega\pi^\circ$	< 1.4 GeV	$62\;(3)\;(4)\cdot 10^{-11}$
$\pi^+\pi^-2\pi^\circ$	< 1.4 GeV	$105\;(4)\;(19)\cdot 10^{-11}$
$2\pi^+2\pi^-$	< 1.4 GeV	$52\;(1)\;(3)\cdot 10^{-11}$
$2\pi^+2\pi^-\pi^\circ$	< 1.4 GeV	$2\;(1)\,(0.4)\cdot 10^{-11}$
$hadrons$	> 1.4 GeV	$905\,(24)\;(46)\cdot 10^{-11}$

Brown & Worstell, 1996

$a_\mu(had, 1)$ improvement by τ data



Assuming isospin invariance to hold, the isovector cross sections of $e^+e^- \rightarrow hadrons$ can be related to corresponding τ decay modes, e.g.:

$$\sigma^{I=1}_{e^+e^-\rightarrow\pi^+\pi^-} = \frac{4\pi\alpha^2}{s}\, v_{1,\ \pi^-\pi^\circ\nu_\tau}$$

$$\sigma^{I=1}_{e^+e^-\rightarrow\pi^+\pi^-\pi^+\pi^-} = 2\cdot\frac{4\pi\alpha^2}{s}\, v_{1,\ \pi^-3\pi^\circ\nu_\tau}$$

$$\sigma^{I=1}_{e^+e^-\rightarrow\pi^+\pi^-\pi^\circ\pi^\circ} = \frac{4\pi\alpha^2}{s}\left[v_{1,\ 2\pi^-\pi^+\pi^\circ\nu_\tau} - v_{1,\ \pi^-3\pi^\circ\nu_\tau}\right]$$

For energy region $s < m_\tau^2$ tau decay data give a factor of ~ 2 improvement in $a_\mu(had;1)$ as compared to the $e^+e^- \rightarrow hadrons$ data alone. Correction of about $(-100 \pm 25) \times 10^{-11}$ for isospin violation has to be applied.

N.B. : some people are skeptical about use of tau data at that level of precision without futher justifications. Particularly they refer to the difference of $1.5 - 2$ sigma between measured value for $Br(\tau^- \rightarrow \pi^-\pi^\circ\nu_\tau)$ and that predicted from e^+e^- data using CVC relations.

$a_\mu(had, 1)$

Calmet et al. (1976): $e^+e^- \to hadrons$ data, integrate fit function	6990 (880)
Barkov et al. (1985): new $e^+e^- \to \pi^+\pi^-$ data (CMD, OLYA)	6840 (110)
Kinoshita, Nizić, Okamoto (1985):	7070 (180)
Casas, Lopez, Yndurain (1985): QCD at high energy, analyticity of pion form factor	7100 (116)
Dubnička, Martinovič (1990): develop and use global analytic models for π and K formfactors, new $e^+e^- \to \pi^+\pi^-\pi^\circ$ data	7048 (115), 7052 (76)
Eidelman, Jegerlehner (1995): enlarge systematic errors (scale factor), trapesoidal integration, more data (ORSAY)	7024 (153)
Brown, Worstell (1996): trapesoidal integration, better correlations treatment	7026 (160)
Alemany, Davier, Höcker (1998): $e^+e^- + \tau$ decay data	7011 (94)
Davier, Höcker (1998): $e^+e^- + \tau$ data and QCD for $\sqrt{S} > 1.8$ GeV	6951 (75)
Davier, Höcker (1998): same + QCD sum rule constraints at low energy	6924 (62)
Further progress (2001 ?): more e^+e^- data from CMD-2 at $\sqrt{S} < 1.4$ GeV and BES at $2 < \sqrt{S} < 4.8$ GeV and more τ data from OPAL and CLEO	?
Further progress (?): upgrade VEPP-2M facility to VEPP-2000 and subsequently more e^+e^- data from CMD-2M and SND at $\sqrt{S} < 2$ GeV and comissioning of KEDR detector at VEPP-4 facility and subsequently more e^+e^- data at $2 < \sqrt{S} < 10.6$ GeV	?

up to date: $a_\mu(had, 1) = 6924\,(62) \times 10^{-11}$

$= 59.39\,(0.53)$ ppm

$a_\mu(had, 2)$

Calmet et al. (1976):	-95 (43)
Kinoshita, Nizić, Okamoto (1985):	-90 (5)
Krause (1997): e^+e^- data	-101 (6)
Alemany, Davier, Höcker (1998): some update, e^+e^- data	-100 (6)

up to date: $a_\mu(had, 2) = -100\,(6) \times 10^{-11}$

$a_\mu(had, lbls)$: hadronic light-by-light scattering

Calmet et al. (1976):	-260 (100)
Kinoshita, Nizić, Okamoto (1985): model of vector meson dominance	49 (5)
Hayakawa, Kinoshita, Sanda (1995,1996): use of low energy effective threshold of QCD, Numbu-Jona-Lasio (NJL) model, hidden local chiral symmetry	-36 (16), -52 (18)
Bijnens, Pallante, Prades (1995,1996): $1/N_c$ expansion, extended NJL model, explicit cutoff at high energy	-110 (50), -92 (32)
Hayakawa, Kinoshita (1998): pseudoscalar (PS) pole dominance, use of off-shell structure of PS-γ-γ anomaly vertex deduced from CLEO data for $\Gamma(\pi^\circ \to \gamma\gamma^*)$	-79 (15)
Further progress (?): lattice calculation of the four-point function ?	?

up to date: $a_\mu(had, lbls) = -85\,(25) \times 10^{-11}$

$a_\mu(weak)$

Standard Model: $a_\mu(weak,1) = 195\,(1)$

uncertainty is due to Higgs mass M_H

Kuraev et al. (1992): $a_\mu(weak,1+2) = 153\,(5)$

substantial correction due to large $\ln(M_W^2/m_\mu^2)$

Czarnecki, Krause, Marciano (1996): $a_\mu(weak,1+2) = 151\,(4)$

more diagrams included

Degrassi and Giudice (1998): $a_\mu(weak,1+2+3) = 153\,(3)$

3rd order and M_H=150 GeV/c^2 rather than 250 GeV/c^2

up to date:

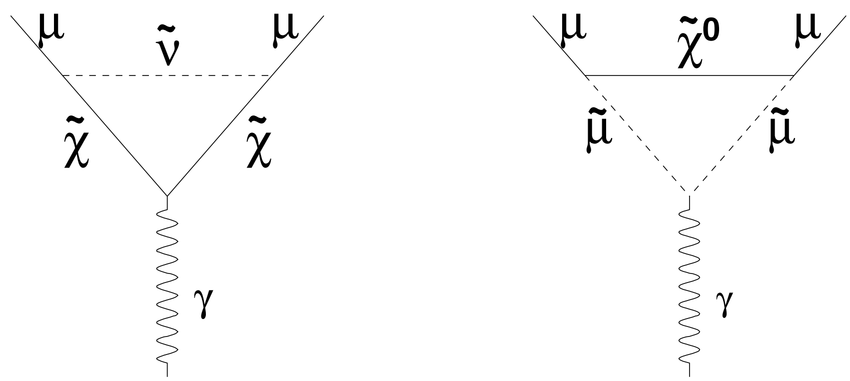
$$a_\mu(weak,1+2+3) = 153\,(3) \times 10^{-11}$$

$$= 1.31\,(0.03)\text{ ppm}$$

Beyond the Standard Model

Many speculative theories predict deviations from the standard model value for a_μ. These include supersymmetry, muon substructure, and anomalous W couplings

The muon $g-2$ value is particularly sensitive to supersymmetry whose contributions to a_μ come from smuon-neutralino and sneutrino-chargino loops:



In the limit of large tanβ, which is the ratio of the vacuum expectation values of two Higgs doublets, and for a degenerate spectrum of superparticles with mass $\widetilde{m}$,

$$a_\mu(\text{SUSY}) \approx 140 \times 10^{-11} \left(\frac{100 \text{ GeV}}{\widetilde{m}}\right)^2 \tan\beta.$$

If we ascribe the difference $a_\mu(\text{exp}) - a_\mu(\text{SM})$ to $a_\mu(\text{SUSY})$, for $\tan\beta$ in the range $4-40$, then $\widetilde{m} \approx 120 - 400$ GeV. This range of mass might be explored in ongoing Run II at Fermilab and (in more details) at LHC collider.